NSNS SPALLATION NEUTRON SOURCE SYSTEM MODEL

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Introduction

This report serves as a description of the Oak Ridge Spallation Neutron Source System Model computer code. This code is meant to serve as a complete systems model which couples all the processes involved in a spallation neutron source (SNS) project. It determines both system parameters and system cost and can be used for quick sensitivity studies. The model allows comparison between parameters and costs of different accelerator options on an equal basis and allows understanding of the relationships between the major accelerator parameters and between these acceleraator parameters and cost. The model was developed for and has been heavily used by the National Spallation Neutron Source (NSNS) project centered at ORNL. This computer code includes models for all the sub-systems of a SNS project, and more importantly, the linkages between the subsystems, which facilitating overall trade-off studies. It is important to appreciate that the code can also be used to cost and optimise other acclerator systems.

The subsystem models used are relatively simple. Typically, fundamental scalings, and rule-of-thumb models are employed using equations with length, energy, magnetic rigidity, power, acceptance, etc. as variables. The model contains subsystem models for (1) accelerator components, (2) experimental systems, (3) buildings and conventional facilities, (4) site power requirements, (5) operation costs, (6) project management, and (7) R&D. A total project cost (TPC) is summed from these subsystem costs with multipliers for ED&I, contingency, and escalation. Of particular concern is the modeling of the accelerator which is the basis for most of the total project cost. The coefficients of the equations in the model are calibrated as necessary to reproduce costs from more detailed studies. Generally the component models are bench-marked to results from previous, more detailed design studies. In particular benchmarks are done with the BNL 5-MW pre-conceptual design study [1], the ANL IPNS upgrade study [2], experience with the ORNL Advanced Neutron Source study [3], as well as results from the ongoing CDR work for the National Spallation Neutron Source project [4]. The purpose of this model is to provide guidance on the cost and performance of various accelerator based neutron sources and is very useful for quickly answering “what-if” questions which inevitably arise in the early stages of such a project, without requiring the efforts of a large design team.

Presently, accelerator options exist for (1) room temperature RF linacs, (2) accumulator rings (AR) without acceleration and sometimes called pulse compression rings, and (3) rapid cycling synchrotrons (RCS). The model is believed to be more accurate for relative

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paraemeters and costs between accelerator options than the absolute overall cost of one particular option.

Each sub-system model includes cost scalings, and where appropriate, calculations for physics and engineering limits. The parameters can be either fixed or varied. The model can be run in a single-pass bench-mark mode, or within an optimization framework. The optimization feature permits identification of minimum cost parameters by varying specified input quantities, which satisfy requisite physics and engineering constraints.

The individual modules for the different sub-systems are described in sections 1 to 6 below. The cost scalings, which use information provided in the previous sections, are described in section 7. These cost scalings explicitly break out the direct costs and the indirect costs, such as overhead, contingency, etc. The code is written using the SUPERCODE driver Shell [5]. This is an interactive driver which includes many useful tools such as optimization and probabilistic risk analysis. The code is written in C++, and runs on workstations and PCs. We stress that this document is not meant to be a computer code user manual, but rather serves to document the underlying equations used in the code.

1. Accelerator Systems

1.1 RF Linac

The components of the RF linear accelerator considered here are depicted schematically in Fig. 1.1. These components are: (1) one or more ion sources (IS) with associated radio-frequency-quadruple accelerators (RFQ), a primary drift-tube-linac (DTL-1), a secondary drift-tube-linac (DTL-2), and a coupled-cavity linac (CCL). These components are discussed below. Note that it is possible to use only one DTL by setting the length of DTL-2 to zero.

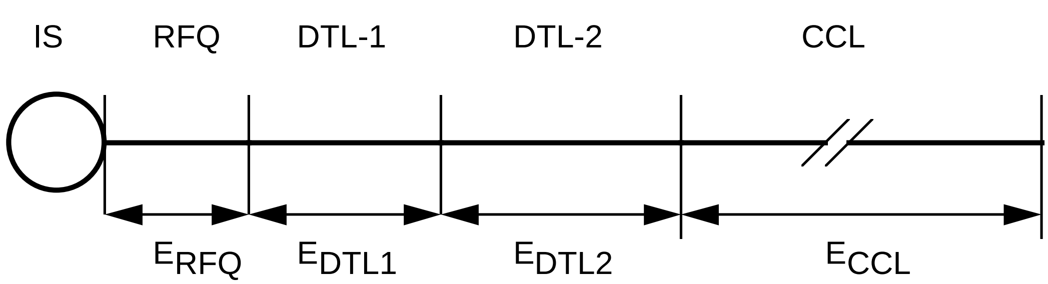


Fig. 1-1. Schematic representation of the components included in the RF linear accelerator.

1.1 .1 Ion Source and RFQ

In addition to the very-short micro structure of a few ns produced by the RF frequency, two basic pulse structures are considered. First is a "macro" pulse in which the linac RF power is turned on and ions are accelerated. This macro pulse is typically one ms long and contains a stream of shorter time scale “chopper-pulses”, separated by short gaps. The chopper pulses are timed to correspond to injection into a ring, and in particular, the orbit circulation time which is typically one μs. The macro pulses are characterized by a macro pulse rate ($_{macro}$), a macro pulse time ($_{macro}$) and the macro pulse duty factor $f_{dutyMacro}$. The shorter chopper pulses are characterized by a peak current ($I_{o\text{-}source}$) per ion source, a chopper pulse rate ($_{chop}$), a chopper pulse time ($_{chop}$), and the chopper pulse duty factor $f_{dutyChop}$. The chopper pulse duty factor is input and is defined as the ratio of the chopper pulse time to the sum of the chopper pulse time and gap time. Specifically the sum of the chopper pulse time and gap time is equal to the ring circulation time at injection. The pulsed nature of this current assumes some sort of chopping capability in the front end of the linac. The peak current in the linac after funneling from N_{source} ion sources is by the equation:

$$I_o = I_{o\text{-}source}\ N_{source}\ .$$

From these inputs, the average current during the chopper pulse time and the time average current into the linac are:

$$\langle I_{chop}\rangle = I_o\ f_{dutyChop}\ T_{bunchRFQ}\ ,$$
$$\langle I_{linac}\rangle = \langle I_{chop}\rangle\ f_{dutyMacro}\ .$$

where $T_{bunchRFQ}$ is the RFQ bunching transmission factor, typically 0.8. The number of chopper pulses per macro pulse is $\tau_{macro}\ f_{dutyChop}/\tau_{chop}$. Nominal inputs for some of these quantities for the NSNS are listed in Table 1.1.1

Table 1.1.1 Sample input assumptions for the ion current calculation.

Peak current (mA)	35
Macro duty factor	0.05
Macro pulse rate (sec^{-1})	60
Bucket pulse time (sec)	7×10^{-7}
RFQ bunching factor	0.8
Chop (chopper) duty factor	0.65

The energy gain in the RFQ is specified (ΔE_{RFQ}), and is nominally 7.0 MeV. Also, the length of the RFQ is (L_{RFQ}) is nominally 3.2 m. Power requirements for the RFQ (P_{RFQwp}) are calculated by assuming a wall plug to beam RFQ efficiency ($_{RFQ}$) of 90%. The average power imparted to the beam, and the wall plug powers are:

$$\langle P_{RFQ}\rangle = \langle I_{linac}\rangle\ \Delta E_{RFQ}$$

$<P_{RFQwp}> = <I_{linac}>\Delta E_{RFQ} / \quad _{RFQ}$.

<u>*1.1 .2 DTL and CCL*</u>

The acceleration efficiencies of the DTLs and the CCL are modeled similarly. The energy gain in each section (ΔE_i) is approximately the structure length of the section (l_i) times the effective accelerating gradient (G_i) and the cosine of the phase angle ($_i$),

$\Delta E_i = l_i \, G_i \cos(\quad _i)$,

where the phase angle $\quad _i$ is the angle between the proton bunch and the peak RF accelerating field. The RF power input into the beam for each linac section is

$<P_{beam\text{-}i}> = <I_{linac}> \Delta E_i$,

where i = DTL-1, DTL-2 and CCL. The total RF power loss to the copper in each linac section is calculated using an effective shunt resistance per unit length[6,7]. This total peak power loss to the copper structure is

$$P_{struct-i} = \frac{\Delta E_i G_i}{R_{shunt-i} \cos(\quad _i)} \ ,$$

and the average power loss rate to the structure is:

$$< P_{struct-i} >= P_{struct-i} \, f_{dutyMacroRF} \ .$$

Here $R_{shunt\text{-}i}$ is the shunt resistance per unit length of the accelerator structure, and $f_{dutyMacroRF}$ is the linac RF macro duty factor which, in order to allow RF filling and stabilization, is nominally set to 1.1 times the ion source macro duty factor. The resistance $R_{shunt\text{-}i}$ depends on details of the accelerator design, and is presently specified as a user input. Typical values used for these quantities are listed in Table 1.1.2. The average total RF power requirement for each accelerating section is

$<P_{RF\text{-}i}> = P_{beam\text{-}i} + <P_{struct\text{-}i}>$,

and the peak RF power requirement for each section is

$$P_{RF0-i} = I_0 \Delta E_i + P_{struct-i} \ .$$

The above analysis provides the power required in the RF system to accelerate the beam with the specified assumptions. From these parameters, wall plug power requirements are calculated by assuming power efficiency factors for the wall plug power and RF power systems, AC to DC conversion, and klystron / wave-guide losses. These efficiencies are presently held constant at a 89% conversion efficiency from AC to DC ($_{AC2DC}$) and a 45% efficiency for DC to launched RF power ($_{RF}$) . Thus the wall plug power requirement for each linac section is:

$P_{RFwp\text{-}i} = \langle P_{RF\text{-}i} \rangle / (\ _{AC2DC}\ \ _{RF})$.

1.1.3 Overall linac parameters

The total length of the linac (L_{linac}) is the sum of the RFQ, DTL, and CCL structure lengths and other lengths. The total linac structure length ($L_{linacStruct}$) is

$L_{linacStruct} = l_{DTL1} + l_{DTL2} + l_{CCL}$.

The linac total physical length of the linac (L_{linac}) is longer,

$L_{linac} = L_{RFQ} + L_{MEBT} + L_{linacStruct} + L_{other}$,

where typically the other linac structure length (L_{other}) is 10 m for empty space and an additional 33% of the CCL structure length. L_{RFQ} and L_{MEBT} are the lengths for the RFQ and the MEBT. The final linac beam energy (E_{Linac}) is the sum for all accelerations, namely

$E_{linac} = \Delta E_{RFQ} + \Delta E_{DTL\text{-}1} + \Delta E_{DTL\text{-}2} + \Delta E_{CCL.}$.

The velocity of the accelerated ion after exiting the linac is v_{linac}. The average wall plug power required to accelerate this beam is

$$\langle P_{linac-wp} \rangle = \langle P_{RFQwp} \rangle + \frac{\langle P_{RF-DTL-1} \rangle + \langle P_{RF-DTL-1} \rangle + \langle P_{RF-CCL} \rangle}{\ _{AC \rightarrow DC}\ \ _{RF}} + \langle P_{coupler} \rangle$$

and the total linac peak RF power requirement is

$P_{maxLinacRF} = P_{RF0\text{-}DTL1} + P_{RF0\text{-}DTL2} + P_{RF0\text{-}CCL} + P_{coupler}$,

where $P_{coupler}$ ($\langle P_{coupler} \rangle$) is the peak (average) bridge coupler power requirement. We use 3.8 MW as the peak coupler power here.

Table 1.1.2 Sample parameters used to calculate the power losses in the RF linac structure.

	DTL-1	DTL-2	CCL
length (m) [a]	7.5	40	500
G (Mev/m) [a]	2.8	2.7	2.8

R_{shunt} (M Ohm/m) (a)	35	30	36.7 - 2400/E_{CCL} (b)
(degree) (a)	30	30	30

Notes for Table 1.1.2:
a - Can be varied in trade study.
b - Scaling from [7]. This can be overridden, and an input value used.

1.2 Ring

The ring module accommodates two types of ring options, either a Rapid Cycling Synchrotron (RCS), or an Accumulator Ring (AR) option. The fast cycling synchrotron serves two purposes: (1) it accelerates the beam to its final energy and (2) it provides the mechanism to compress a long pulse of protons from the linac to a short pulse of protons on the target. The accumulator ring does not accelerate the beam, but provides the mechanism to compress the beam and deposit a short pulse to the neutron-producing target. The model assumes that there are "N_{ring}" rings of similar type. Most of the modeling is independent of the type of ring.

1.2.1 Ring Geometry

The ring geometry modeling generally follows the prescription of A. Ruggerio [8]. The layout is determined by specifying the ring super-periodicity (S_{ring}), the number of elements per half super-period structure, and the length of each type of element. Each super-period is assumed to be anti-symmetric about its midpoint. The different ring elements which are presently allowed and their characteristics are listed in Table 1.2.1.

Table 1.2.1 Allowed ring elements in the model.

Element	Number per ½ period	Length per element (m)
Dipoles	$N_{dipole\text{-}HL}$	l_{dipole}
Normal quadrupoles (i.e. FODO type)	$N_{quad1\text{-}HL}$	l_{quad1}
Insertion type 1 quadrupoles	$N_{quad2\text{-}HL}$	l_{quad2}
Insertion type2 quadrupoles	$N_{quad3\text{-}HL}$	l_{quad3}
Short drifts (typically between the normal quadrupole and dipole)	$N_{shortDrift\text{-}HL}$	$l_{shortDrift}$
Long drifts type 1	$N_{insertDrift1\text{-}HL}$	$l_{insertDrift1}$
Long drifts type 2	$N_{insertDrift2\text{-}HL}$	$l_{insertDrift2}$

The total number of dipoles per ring and the total length of the dipoles are

$N_{dipole} = 2\, S_{ring}\, N_{dipole\text{-}HL}$,

$L_{dipole} = N_{dipole}\, l_{dipole}$.

The total number of quadrupoles per ring, and the total length of the quadrupoles are

$N_{quad} = 2\, S_{ring}(N_{quad1\text{-}HL} + N_{quad2\text{-}HL} + N_{quad3\text{-}HL})$,

$L_{quad} = 2\, S_{ring}(N_{quad1\text{-}HL}\, l_{quad1} + N_{quad2\text{-}HL}\, l_{quad2} + N_{quad3\text{-}HL}\, l_{quad3})$.

The total drift length per ring is

$$L_{drift} = 2\, S_{Ring}(N_{shortDrift\text{-}HL}\, l_{shortDrift} + N_{insertDrift1\text{-}HL}\, l_{insertDrift1} + N_{insertDrift2\text{-}HL}\, l_{insertDrift2}) .$$

The total circumference of the ring is

$L_{ring} = L_{dipole} + L_{quad} + L_{drift}$.

Typically, to allow variation in the ring circumference, the short drift length ($l_{shortDrift}$) is allowed to vary. The bending radius of the dipole magnets is given by

$r_{bend} = L_{dipole} / 2$

1.2.2 Injection

Beam is injected into the ring during the linac macro pulse and the number of injected turns is given by the equation:

$n_{turnsInj} = \tau_{macro}\, v_{linac} / (n_{harmonic}\, L_{ring})$,

where $n_{harmonic}$ is the harmonic number, that is, the number of chopped bunches per revolution which is nominally one. The number of protons injected and captured per ring is

$n_{partRing} = \tau_{macro}\, T_{lossInject} <I_{chop}> / (N_{ring}\, e)$,

and the average beam current extracted from the ring is

$<I_{ring}> = <I_{linac}> T_{lossInject}$,

where e is the proton charge and $T_{lossInject}$ is the transmission fraction of beam injected and captured in the ring and is typically in the order of 95%. The injection time is simply:

$$_{inject} = n_{turnsInj} L_{ring} \, / \, v_{linac} \ .$$

The number of protons injected in the ring can be limited by the betatron tune shift depression, $\Delta \ _{inj}$ .This important limit is given by the equation,

$$\Delta \ _{inj} = \frac{n_{partRing} \, r_p}{2 \ {}^{2}_{inj} \ {}^{3}_{inj} \ B_f \ _{inj}} \ ,$$

where $r_p$is the classical proton radius, B_f is the bunching factor which is the average current divided by the peak current and is typically 0.3, and $_{inj}$ is the total beam emittance in the ring at injection in units of π-m-rad. A similar calculation for tune depression is done for the extraction parameters, in-which the extraction emittance is scaled as

$$_{ext} = \ _{inj} \times \frac{_{ext} \ _{ext}}{_{inj} \ _{inj}} \ .$$

Typically, the allowable tune shift is input, and the resultant emittance at injection is calculated. This emittance value is typically subsequently used in sizing the magnet gaps which are described below.

1.2.3 RCS Acceleration and RF power

The acceleration period in a RCS is

$$\tau_{accel} = (N_{ring} \, / \, \nu_{macro}) \, f_{dutyRing} \ ,$$

where N_{ring} is the number of rings, $_{macro}$ is the repetition rate of the synchrotron(s), and $f_{duty\text{-}RF}$ is the acceleration duty factor of the synchrotron, nominally 50% . The acceleration duty factor is defined as the fraction of the ring cycle time during which proton acceleration occurs. The approximate number of transits around the ring during this acceleration period is

$$N_{ringTrans} = < v_{ring} > \ _{accel} \, / \, L_{ring} \ ,$$

where $<v_{ring}>$ is the average velocity in the ring during acceleration. An initial estimate for this is discussed below. The total energy added during acceleration is

$$\Delta E_{ring} = f_{rRingAccel} \, N_{ringTrans} V_{RFTot} \sin(\ _s)2 \, /$$

where $f_{ring\text{-}accel}$ is an adjusting factor for non-sinusoidal voltage envelope shapes and is nominally one, $_s$ is the synchronous phase angle, and V_{RFTot} is the sum of the peak cavity RF voltages around the ring which is the product of N_{RFRing} , the number of RF cavities, and V_{maxCav} , the peak voltage per cavity. Transit time effects are ignored. The $2/\pi$ factor is the average to peak ratio for an assumed sinusoidal wave form of the RF power. The final beam energy is

$$E_{ring} = E_{linac} + \Delta E_{ring} .$$

From these equations, the bending magnetic field and field ramp rate can be calculated However, the required voltage per turn around the ring is proportional to the field ramp rate dB/dt

$$V_{RFTot\,\mathrm{Re}q} = L_{ring} r_{bend} \frac{dB}{dt} \sin(\quad _s) .$$

Values for V_{RFTot} and a guess for the average proton velocity $<v_{ring}>$ are input. Then using the equations for the field ramp rate dB/dt, the required voltage $V_{RFTotReq}$ is calculated. The guess for the average velocity during acceleration is iterated until $V_{RFTot} = V_{RFTotReq}$. Also, it is possible to vary V_{maxCav} to match a desired final beam energy (E_{ring}). The average and peak RF power to the beam in the ring(s) are :

$$< P_{ringBeam} >= n_{partRing} \Delta E_{ring} e \quad _{macro} N_{ring} ,$$

$$P_{ringBeam\,0} = \frac{n_{partsRing} \Delta E_{ring} e \quad _{macro}}{N_{ring} f_{dutyRing}} \Big/ 2 .$$

In the case of an accumulator ring, no net energy or power is supplied to the beam, but an average energy of 0.4GeV per proton-per pulse is assumed to be required to provide bunching in the ring, in order to calculate RF power requirements. The total RF power requirements($<P_{ringRF}>$, and $P_{ringRF0}$) are increased from the above values by a factor of $f_{ringACLossRF}$, nominally 1.21, to account for losses to ferrite materials etc. The average wall plug power ($<P_{ring\text{-}wp}>$) calculation assumes an efficiency of 60% from wall plug power to RF power available for the beam.

As the beam velocity varies during acceleration, the RF frequency must also vary to maintain synchronization. The RF frequencies at injection and extraction respectively are:

$$_{inject} = v_{linac} n_{harmonic} \,/\, L_{ring} \text{, and}$$

$$_{extract} = v_{ring} n_{harmonic} \,/\, L_{ring} .$$

Where v_{linac} and v_{ring} are the velocities at injection and extraction, respectively.

1.2.5 Magnets

1.2.5.1 Dipoles

The dipoles are primarily characterized by their length (l_{dipole}), gap (g_{dipole}) and magnetic field. The field required to provide the bending radius at injection and extraction are

$$B_{bendInj}(T) = \frac{{}_{Inj} M_{beam}(AMU) \mathrm{v}_{Linac}(m/s)}{e r_{bend}(m)}$$, and

$$B_{bendExt}(T) = \frac{{}_{Ext} M_{beam}(AMU) \mathrm{v}_{Ring}(m/s)}{e r_{bend}(m)}$$.

The peak field ramp rate during acceleration is:

$$\frac{dB_{bend}}{dt}\left(\frac{T}{s}\right) = \frac{\left(B_{bendExt} - B_{bendInj}\right) \times {}_{macro} \times \frac{}{2}}{N_{ring} \times f_{dutyRing}}$$

We also calculate a minimum dipole gap size, based on the beam emittance, following the method suggested by A. Ruggiero [8]. First the minimum ring acceptance ($_{ring}$)is calculated based on the beam emittance,

$$_{ring} = {}_{inj} R_{accept} ,$$

where R_{accept} is a safety factor, nominally = 8. Then the minimum acceptable dipole gap is calculated as

$$g_{dipoleMin} = 2\sqrt{{}_{ring} \quad {}_{dipole}} + d_{vv} ,$$

where the dipole beta value is scaled from the quadrupole beta value (see below) as $_{dipole} = 0.7 \quad _{quad}$, and d_{vv} is the vacuum vessel thickness (=0.01m for accumulator rings and = 3 cm for synchrotrons). For optimization runs, it is required that the dipole gap used for sizing the magnets be constrained by:

$$g_{dipole} \geq g_{dipoleMin} .$$

Details of the dipole size and power requirement scalings are shown in Appendix A.1.

1.2.5.2 Quadrupoles

The quadrupoles are characterized by a bore size (b_{quad}), a gradient ($B_{quadGrad}$), and a beta value ($_{quad}$). The total quadrupole power requirement per ring is scaled as:

$$P_{quadTot}(W) = 6.5\times 10^{4} N_{quad} \left(B_{quadGrad}(T/m)\, b_{quad}^{2}(m)\left[< l_{quad} > (m) + 15 b_{quad}(m)\right]\right)$$

where $<l_{quad}>$ is the average quadrupole length per ring. This approximation is found to match several existing and proposed studies. The quadrupole gradient is nominally 3 T/m. We also estimate the minimum quadrupole bore ($b_{quadMin}$), in a similar manner as for the dipoles above. Namely,

$$b_{quadMin} = 2\sqrt{\ _{ring}\ \ _{quad}} + d_{vv}\ ,$$

where the quadrupole beta is nominally 15m.

The total power requirement for the ring magnets is then:

$P_{ringMag} = P_{quadTot} + P_{dipoleTot}$.

2. Experimental Systems

This module specifies the target stations, moderators, neutron beam lines and instruments. Output includes the total number of instruments, space requirements, cryogenic power requirements, shielding requirements and cost. These systems are modeled through a set of classes constructed with the attributes discussed below.

The target station characteristics are described in Table 2.1. Each target in can have a number of moderators surrounding it. Six moderators are allowed per target station.

The moderator characteristics are described in Table 2.2. Presently, the number and type of the moderators on each target station moderator is simply specified. The total cryogenic powers are calculated here, based on the inputs from the moderator specification. Each moderator can in turn have 3 beam-lines on it. The total number of ambient temperature moderators ($N_{ambientMods}$) and cryogenic temperature moderators ($N_{cryoMods}$) is tracked. The total power deposited in cryogenic moderators is also calculated (H_{cryo}).

The beam-line characteristics are listed in Table 2.3. From these input characteristics, the total neutron guide length is calculated, along with the total beam shielding volume. This shielding is distinct from the target shielding volume which is presently used in costing. The beam shielding described here is probably not very accurate. The shield volume calculation assumes a 2-m high by 1-m wide enclosed area, so the total shield volume is

$$V_{shield} = \sum_{i} L_{beam-i} \times t_{shield-i} \times (2+2+1)\ ,$$

where the summation i is over all beam lines, $L_{beam\text{-}i}$ is the length of the i'th beam line, and $t_{shield\text{-}i}$ is the shield thickness around the beam. Each beam line may have up to 2 instruments on it.

These instruments are also specified by the user. Their characteristics are listed in Table 2.4. Most of these characteristics are self explanatory, but the active status specifies requires some discussion. The active status is included to allow inclusion of "space" for an experimental station, while not including the cost of the experiment per se. If this switch is set to "phantom", the space requirements are included in other modules, such as building layout. However, with the phantom setting, staff and costs, are not included in the plant totals.

Table 2.1. Target station characteristics

Characteristic	Comment
frequency	pulse rate of the target station
moderators	Number of moderators on the station
Cost	Construction cost

Table 2.2. Moderator characteristics

Characteristic	Comment
Target	Target moderator is surrounding
Poisoned	Whether neutron absorption is included
Coupled	Designed for short pulse to experiments
Coolant Type	Cryogenic (He, Methane) or Ambient (H2O) coolant
beams	Number of beams on the moderator

Table 2.3 Beam-line characteristics

Characteristic	Comment
moderator	Moderator beam is on
shieldThick	Shield thickness surrounding beam [m]
dist2Target	Beam line length [m]
guide	Switch for neutron guide (True / False)
shutter	Switch for shutter (True / False)
chopper	Switch for chopper (True / False)
instruments	Number of instruments on the beam

Table 2.4 Instrument characteristics

Characteristic	Comment	Nominal value
Moderator	Moderator experiment is on	---

Area	Floor space required (m^2)	50
Cost	Cost of the instrument [M$]	1.5
dist2Beam	Distance from beam to instrument (m)	10
Active Status	On, Off, or Phantom	On

3. Buildings:

These following are building areas based on estimates for the NSNS project and site [9] . These values give an estimate for the size and number of buildings needed for a greenfield site for this type project.

Injector Hall:

$A_{injectHall}$ (m^2) = 604.

Front End Service Building area :

A_{FEServ} (m^2) = 935.

Linac support building area :

This building area includes the buildings that house the klystrons and any connecting tunnels between them.

$A_{bldgLinKly}$ (m^2) = 9.1 L_{linac}
$A_{LinacPump}$ (m^2) = 1.05 L_{linac}

Linac Service Building area :

This building area is for klystron and magnet testing.

$A_{bldgLinServ}$ (m^2) = 1530.

Electronics Test Building area :

This building area is for electronic equipment testing.

$A_{elecTest}$ (m^2) = 610.

Ring Support and Service Buildings:

$A_{ringGrnd}$ (m^2) = 654 N_{ring} (for HEBT, TBST, injection hall, and extraction hall).

$A_{ringService}(\mathrm{m}^2) = 505\ N_{ring}$ (for electronics, assemble, and vacuum labs).

Transfer line tunnel length:

Transfer lines from linac to dumps, rings, and transfer from ring to targets.

$$L_{transferTunnel} = L_{Linac2Ring} + N_{Targets} L_{Ring2Targ} + L_{Ring2Dump}.$$

An option exists to scale the linac-to-ring-transfer length from the reference design value as:

$$L_{Linac2Ring} = 180\ \mathrm{m}\ (L_{Ring}/208.5)\ 3./\ S_{ring}\ .$$

Experimental Hall

One experimental hall per target station is assumed with a total area ($A_{expHall}$) of 4150 m^2. Presently, this space is not scaled. Also this space is about half of that used in the BNL design [1]. The experimental hall area includes space for the target, neutron beam-lines and instruments as well as research support labs.

Administration building:

This building houses administrative offices, and has an area

$A_{admin}\ (\mathrm{m}^2) = 3660.$

Control building:

$A_{control}\ (\mathrm{m}^2) = 670.$

Research Support building:

$A_{resSupl}\ (\mathrm{m}^2) = 840.$

The resulting total building floor area is:

$$A_{bldgsTot}\ (\mathrm{m}^2) = A_{resSupl} + A_{control} + A_{Admin} + A_{expHall} + A_{ringGrnd} + A_{ringService} + A_{elecTest} + A_{bldgLinKly} + A_{linacPump} + A_{bldgLinServ} + A_{FEService} + A_{injectHall}.$$

Another useful building area characteristic is the total building and tunnel “footprint” on the ground. For this purpose, we divide the building floor areas above by the appropriate number of elevations per building, and use a 3.7-m width for the linac and transition tunnels, and a 10-m width for the ring tunnels, leading to

$A_{bldgsFoot}$ (m^2) = $A_{resSupl}$ + $A_{control}$ + A_{admin}/3 + $A_{expHall}$ + $A_{ringGrnd}$ + $A_{ringService}$ + $A_{elecTest}$ + $A_{linacPump}$ + $A_{bldgLinKly}$ + $A_{bldgLinServ}$ + $A_{injectHall}$./2 + $A_{FEService}$ + (L_{linac} + $L_{transferTunnel}$) * 3.7 + L_{ring}* 10.

<u>Target Shield Mass</u>

The target shield is calculated assuming a cylindrical geometry. Nominally for a 1-MW beam, the cylinder has a half height of 5 m, and a radius of 4.44 m. The radius and height are scaled with beam power, using a 20-cm e-folding length, so that these dimension scale as

r_{shield} = 4.44m + ln($P_{beamRing}$ /1MW) 0.2m.

The shield mass (M_{shield}) is calculated using 7900 kg/m^3 for iron.

<u>4. Power Requirements:</u>

The total beam power is first calculated, accounting for the possibility of an additional long pulse operation in parallel with the short pulse power from the rings.

$P_{beamTot} = P_{beamLP} + P_{beamRing}$.

The power to run the cryogenic equipment is scaled as:

$$P_{cryo}(W) = 2x10^{-3} P_{beamTot}(W)\left(N_{HeCooledMods}\left[\frac{\frac{293}{18}-1}{0.15}\right] + N_{MethaneCooledMods}\left[\frac{\frac{293}{95}-1}{0.30}\right]\right).$$

This equation assumes 2 KW is deposited in each moderator per MW of proton beam power incident on the target, and operating temperatures of 18 K and 95 K for the He and methane cooled moderators, respectively. Also a heat removal efficiency of 15% and 30% relative to the ideal Carnot cycle is assumed for the He and methane cooled moderators, respectively. The pumping power is calculated assuming a double loop system for the target cooling, and single loops system for all other needs. Water flow rates of the systems are estimated from

$$Flow\left(\frac{m^3}{\sec}\right) = \frac{10^{-3} P(W)}{4180\Delta_T(C)}.$$

For the target primary loop, a temperature drop of 11 ^{o}C is assumed, and the power removed is $P_{beamTot}$. For the secondary loop, a temperature drop of 17 ^{o}C is assumed, and the power removed is $<P_{linac\text{-}wp}> + <P_{Ring\text{-}wp}> + P_{RingMag} + P_{cryo} + P_{BOP}$. The pumping power is

$$P_{pump}(W) = \frac{\sum_{Primary+secondary} FlowRate\left(\frac{m^3}{\sec}\right)\Delta_P(Pa)}{0.9},$$

where the pressure drop is assumed to be 7x10^5 Pa (100 psi). The miscellaneous building power for HVAC, lights, receptacle, etc. is estimated as

P_{bldgs} = 200 (W/m^2) $A_{bldgsTot}$ +1000 (W/m) ($L_{transferTunnel} + L_{ring} + L_{linac}$),

The resistive site power installed capacity is estimated as:

$$P_{site} = <P_{linac\text{-}wp}> + <P_{Ring\text{-}wp}> + P_{RingMag} + P_{cryo} + P_{BOP} + P_{Bldgs} + P_{KlysTest} + P_{pump}$$

where P_{BOP} the miscellaneous power requirement for the balance of plant which has been set to 8.5 MW and $P_{KlysTest}$ is the klystron testing building power which has been set to 2 MW. The peak MVA requirement is set to the site requirement ($P_{MVA} = P_{site}$).

Finally, the water usage rate is estimated from the site power, assuming 1000 BTU/lb of water, and introducing an additional factor of 2 to account for blow-through to prevent precipitate buildup,

$$H_2O_{usage}\left(\frac{m^3}{\sec}\right) = \frac{2x10^3 P_{site}}{2.33x10^6 \left(J/kG\right)}.$$

5. Operations

Operational costs modeling is based largely on the rationale described in the note of Ref. [10]. In this note operating staff levels are derived, based in part on the experience from the ANS project as described in [11]. Some items are scaled with input from other modules as noted. Obviously some WBS categories have changed relative to ANS and these changes are described below. Generally, the level of detail included here is not as great as that in Ref. [11]. Non-research staff levels scale with the SNS beam power as:

$$personnel = Nominal\ level \times \left(\frac{P_{beamTot}}{P_0}\right)^{0.25},$$

where the nominal power level P_0 is taken to be 0.40 MW, picked so that the non-scientific staff level for a 1 MW facility is approximately 200 people. This scaling is not applied to items in which the power level is already accounted for explicitly. Finally, the costs reported here are escalated from the 1992$ reported in ref. [10] to 1995$ using a factor of 1.07, and that the FTE costs reported here do not include laboratory overhead.

Administrative Support

This category is entirely staff costs. The number and cost rates for administrative support is described in Table 5.1

Table 5.1 Scalings for administrative support costs.

	Number of Personnel	Cost per Personnel [k$/yr] (a)
Maintenance	$5\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	38.5
Operations	$8\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	34.7
Training	$2\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	34.7
Research Operations	0.15 x number of instruments (b)	34.7
Management & Planning	$2\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	34.7

a - Lab overhead is not included.
b - ANS had 24 administrative research operations personnel and 48 experiments.

Management and Planning

This category is entirely staff costs. The number and cost rates for management and planning is described in Table 5.2

Table 5.2 Scalings for Management costs

	Number of Personnel	Cost per Personnel [k$/yr] (a)
Maintenance	$4\times\left(\frac{P_{beam}}{P_0}\right)^{0.25}$	71.5
Health & Safety	$1\times\left(\frac{P_{beam}}{P_0}\right)^{0.25}$	99.0

Training	$1\times\left(\frac{P_{beam}}{P_0}\right)^{0.25}$	57.8
Research Operations	0.104 x number of instruments(b)	137
Operations	$4\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ (c)	84.3 (d)

a - No lab overhead included.
b - ANS had 5 management personnel and 48 experiments.
c - ANS detritiation personnel not included.
d - Average of ANS values for this category.

Maintenance

This category is entirely staff costs. The ANS philosophy of using ORNL pool personnel is followed here. These are generally based on the HIFR experience. An additional 20% factor, as per ANS, to account for additional training is not included. The number and cost rates for maintenance staff is described in Table 5.3

Table 5.3 Maintenance staff requirements.

	Number of Personnel (a)	Cost per Personnel [k$/yr] (a)
Craft	$26\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	87.3
Non-Craft	$12\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$	87.3

a - Assumed to use ORNL employees.

Quality Assurance

QA costs are calculated assuming a 108 k$/yr/person and $5\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ FTE for QA personnel.

Training

Training costs are calculated assuming a 60.5 k$/yr/person and $5\times\left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ FTE for training personnel.

Health & Safety

Presently, the nominal ANS values are used. The costs are:

$$Health\&Safety(k\$/yr) = 6FTE\left(\frac{P_{beamTot}}{P_0}\right)^{0.25} \times 100\frac{k\$}{FTE} + 100k\$$$

The constant cost adder is for bio-assay equipment, health physics supplies, and instrument calibration.

Utilities

Utility cost include power, steam, water and waste disposal. The power costs are calculated for the accelerator including all losses, pumping, cryogenic plant, and balance of plant as described in Section 4. Values for the peak power requirements are calculated in the power module. The average annual power requirements are scaled as:

$$P(W-hrs) = 8760\left(\frac{hrs}{yr}\right)\left(f_{capacity}\sum_i P_{peak-i}(W) + (1-f_{capacity})\sum f_{off-i}P_{peak-i}(W)\right)$$

The first term in the brackets is the power during normal operation which is the peak value. The second term represents the power requirements during maintenance periods. The fraction of time for normal operations ($f_{capacity}$) is assumed to be 0.65. The fractional power requirements during maintenance periods are shown in Table 5.4.

Table 5.4 Fractional powers assumed during maintenance periods.

System	Fractional power
Accelerator	0
Cryogenic plant	0.1
Pumps	0.5
BOP	0.76

These scalings generally follow those of the ANS.

Power costs are calculated assuming a Cost of Electricity (COE) of 0.0509 \$/kW-hr in \$1992. Steam costs are calculated using 0.0196 \$/kg, and the primary requirement is assumed to be HVAC which is nominally set at 30.844 kg/hr. This usage rate is applied for 65% of the year, as per Ref. [3]. Note that no detritiation or reactor building evaporator steam requirements are included. The water use calculation is described in Section 4, and is applied for $f_{capacity}$ fraction of the year. The water cost is taken to be 0.189 \$/m^3. No water use is presently included for the maintenance. Waste disposal costs are fixed at 83 k\$/yr, and cover oily and solid wastes. At present, no radioactive waste disposal cost is included. These utility costs are applied to the materials cost category.

Replaceable Items

Replaceable item cost include computer related equipment, major equipment replacement, cryogenic facility operation, and spare parts. The computer related equipment is taken to be 200 k$/yr, about one third of the ANS value, as there is no Safety-Class-1 hardware/software requirement. The major equipment replacement costs are assumed to be target assemblies, target pressure vessels, moderator assemblies, and klystrons (presently set to half the accelerator RF hardware costs). The hardware components of these costs are divided by an assumed lifetime to calculate the major equipment replacement costs. The lifetime fluences assumed are: moderator assembly = 10 MW-yr, target pressure vessel = 25 MW-yr, and klystrons = 10 yr. The target lifetime is based on information from ISIS, and uses a proton fluence limit of 1752 mA-hr, and assumes a 4-day replacement time. Thus the number of targets required per year is:

$$Targets\,/\,year = \frac{365 \times f_{capacity}}{\dfrac{1752mA - hr \times E_{beam}(Gev)}{P_{beam}(MW) \times 24} + 4}$$

The present state of cost estimation lacks the detail to do a bottoms up spare parts estimate. Rather the ANS philosophy of charging 80% of 3% of the cost elements with moving parts is used which includes the water systems and 20% of the moderator costs. The cryogenic facility operation costs are scaled as

$$Cryo\,Facility\,Costs(\$\,/\,yr) = 7x10^{5}\left(\frac{CryoPower(W)}{ANS\ value}\right)^{0.6}$$

Security

The ANS assumptions are adopted here, namely $3.5 \times \left(\frac{P_{beam}}{P_0}\right)^{0.25}$ security personnel, at 65 k$/yr.

Accelerator Operations

The operation costs are broken into 3 segments, and the ANS values are generally used. The main control costs assume $40 \times \left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ FTE at 82 k$/yr (2/3 of ANS value). The support personnel costs assume $4 \times \left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ FTE at 50 k$/yr (ANS value without detritiation staff). The machine technology costs assume $29.5 \times \left(\frac{P_{beamTot}}{P_0}\right)^{0.25}$ FTE (mostly engineers) at 80.6 k$/yr.

Research Operations

Two scientific FTE per active instrument is assumed, plus support personnel of 1.2 FTE per active experiment. This latter term includes one technician per instrument and one secretary per five other personnel. An annual cost of 135 k$/yr is assumed for all personnel.

Initial Purchases

Provisions are also made for the initial purchase of additional equipment needed to ensure operation during commissioning. These elements are typically items likely to fail, which have long manufacturing lead times. These elements include one mercury target assembly, and one set of moderators. These moderator costs are taken to be 7% of the entire cryogenic moderator assemble cost and 10% of the entire ambient temperature moderator assembly.

6. Project Management

In this module, the numbers of project support staff are specified. As discussed later in the costing description, these numbers are used as a basis for determining the breakdown of the various project support personnel. There is an option to scale the absolute number of project support personnel so that the project support costs are a specified fraction of the construction costs. In this case the information provided here is simply a basis to pro-rate the breakdown of the project support costs among the various sub-categories. A nominal project life of 6 years is assumed. When a variable staffing level over the project life is required a triangular spending profile is assumed, with a base at the minimum FTE requirement. Thus the equivalent number of FTE's for a variable staffing category is:

$$FTE_{total} = L_{project}\left(N_{\min} + \frac{N_{\max} - N_{\min}}{2}\right)$$

where $L_{project}$ is the project life (yr), N_{min} is the minimum number of FTE's/yr and N_{max} is the maximum number of FTE's/yr. For categories with constant staffing levels, the total FTE's are simply the project life times the FTE's/yr. An FTE rate of 132 k$/yr is assumed which does not include laboratory overhead. The number of staff listed below was normalized to reproduce the project support costs estimated in the February 1996 NSNS cost estimating exercise.

Project Management and Administration

This category includes the top level of project management. Four top level managers (Project director, Project manager, secretary, Science advisor, and finance manager) are assumed at 1.0 FTE each over the project life. Additional staffing areas in this category with variable requirements are:

	Minimum Level	Maximum Level
Technical Management	3.75	3.75
Technical Support	6.0	10.0
AE support	4.7	11.0
Construction Management	4.0	18.75
Sub-contract administration	0.5	1.0
Other lab support	1.0	2.5
Other DOE Lab support	14.75	14.75

Costs are calculated with the above staffing levels assuming an average of 105 k$/FTE. The required FTE's have been adjusted to match more detailed costs, and a nominal Lab overhead rate of 32.25% is applied to all cases except:

- The A/E support uses a subcontract rate of 5.9%, and
- The Other DOE Lab support uses an overhead rate of 32.25 % (same as ORNL)

Systems engineering

This category is set at 26 FTE for a 6 year project. We scale with project length by assuming an average of 4.33 FTE/yr of the project.

Safety

This category is set at 11.5 FTE, integrated over the project life. [12]

Environmental and Waste Planning

The environmental permitting is assumed to be 0.4 M$ + 1.0 M$ for the Environmental Impact Statement.

Quality Assurance

The QA requirements are assumed to be lower than those of ANS. 46 FTE, integrated over a 6 year project life, are assumed. A scaling of 7.7 FTE per year is incorporated in the model.

Regulatory Compliance

This cost is fixed at 1.3 M$.

7. Costs

7.1 General Description

The cost module takes input from the various physics and engineering modules and scales the costs. Costs for each item are broken down into the following sub-categories:

Cost Category	Comment
Engineering	ED&I costs
Hardware	Material Costs
Labor	Labor costs associated with manufacture and installation
Construction Management	Covers costs of managing the construction
Direct subtotal	Sum of Engineering + Labor + Hardware + Construction Management
Engineering overhead	Overhead costs associated with ED&U
Hardware overhead	Overhead costs associated with hardware
Subcontract overhead	Overhead costs associated with Lab subcontracting
Overhead subtotal	Sum of all overhead costs
Tax	Tax on materials
Contingency	Contingency on (Direct total + Overhead subtotal + Tax)
Escalation	Escalation on (Direct total + Overhead subtotal + Tax + Contingency)
Total	Overhead subtotal + Direct subtotal + Tax + Contingency + Escalation

By default, the engineering ($C_{Eng\text{-}i}$) and labor ($C_{Lab\text{-}i}$) costs are scaled as a factor ($f_{Eng\text{-}i}$, $f_{Lab\text{-}i}$) of the hardware costs ($C_{Hard\text{-}i}$). The subscript *i* here refers to the particular WBS element. Cost scalings which are independent of the Hardware costs can be provided directly for these items with $C_{Eng0\text{-}I}$ and $C_{Lab0.}$ Thus

$C_{Eng\text{-}i} = C_{Eng0\text{-}i} + f_{Eng\text{-}i}\ C_{Hard\text{-}i}$,
$C_{Lab\text{-}i} = C_{Lab0\text{-}i} + f_{Lab\text{-}i}\ C_{Hard\text{-}i}$.

Construction Management costs may either be input directly, or scaled with the ED&I costs:

$$C_{constMan\text{-}i} = C_{constMan0\text{-}i} + f_{constMan\text{-}i}\ C_{Eng\text{-}i}\ .$$

A subtotal of the sum of Engineering + Labor + Hardware + Construction Management is stored in the Direct sub-category. Separate overhead rates are applied to the Hardware ($f_{hardOv\text{-}i}$), the Engineering ($f_{engOv\text{-}i}$) and the Labor categories ($f_{labOv\text{-}i}$) to calculate overhead costs ($C_{engOv\text{-}i}$, $C_{hardOv\text{-}i}$, $C_{labOv\text{-}i}$)

$C_{hardOv\text{-}i} = f_{\ hardOv\text{-}i}\ C_{Hard\text{-}i}$, and

$$C_{engOv\text{-}i} = f_{\ engOv\text{-}i}\ C_{Eng\text{-}i}$$

$$C_{labOv\text{-}i} = f_{\ labOv\text{-}i}\ (C_{Lab\text{-}i} + C_{constMan\text{-}i})$$

The total of these overhead costs is stored in an Overhead subtotal. Nominally, an overhead rate of 3% is applied to hardware, and 32.25% is applied to Engineering and Labor and construction management costs are assumed to be subcontracted and use a 5.9% overhead. Also, all WBS category 8 elements use overhead rates of 5.9% for Labor and Hardware, as these WBS elements are expected to be subcontracted. A separate tax category is provided for the taxes on the purchased materials (C_{tax-i}). This is calculated assuming an 8.25% tax rate. A contingency factor (f_{cont-i}) is applied to the sum of the (Hardware + Engineering + Labor + Installation + Overhead + Tax) to calculate a contingency cost for each WBS element (C_{cont-i})

$$C_{cont-i} = f_{cont-i} \left(C_{Eng-i} + C_{Lab-i} + C_{Hard-i} + C_{constMan-i} + C_{engOv-i} + C_{hardOv-i} + C_{labOv-i} + C_{tax-i} \right) .$$

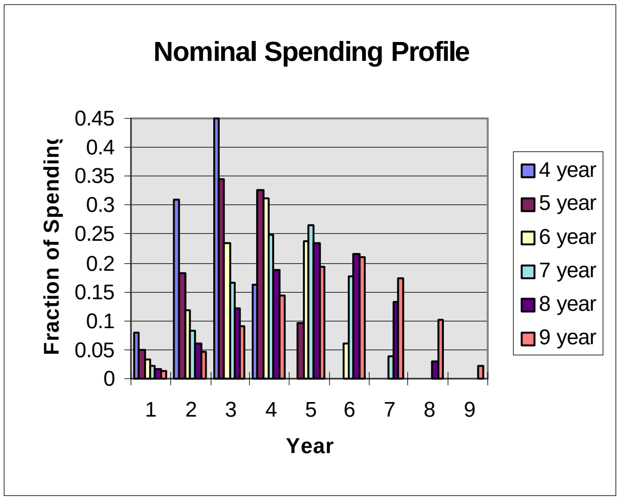
The default contingency factor is 0.25.

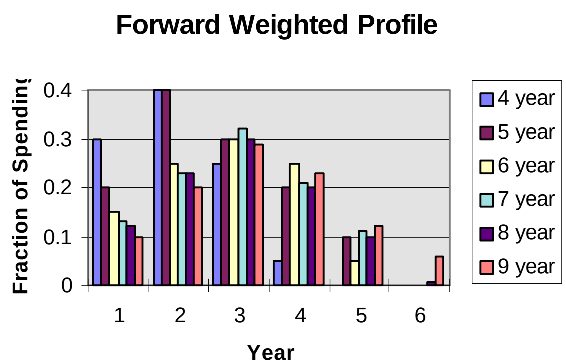
Cost escalation is calculated, using an assumed spending profile for each WBS element. Presently these spending types are specified at the Level 2 WBS. Three types of spending profiles are provided: (1) a default centrally peaked distribution, (2) a forward weighted distribution, and (3) a rear weighted profile. The R&D WBS elements use a forward weighted spending profile, the Pre-Operation cost (WBS 1.11.6) uses a rear weighted spending profile, and all other WBS elements use the centrally peaked spending profile. These profiles are illustrated in Fig. 7.1. The escalation factor (f_{escal}) is calculated for each WBS element as the weighted sum of the inflation and spending rate,

$$f_{escal} = \sum_{project\ years} f_{spend-i} f_{\inf late-i} ,$$

where $f_{spend-i}$ is the fraction of spending during year i (see Figure 7.1) and $f_{inflate-i}$ is the cumulative inflation index of year i. The inflation index is calculated from the January 1996 DOE guidelines for Energy Research and Nuclear projects. The inflation rates from these guidelines are shown in figure 7.2. The project life is specified by a start year (nominally 1998) and a project life (nominally 6 years).

Figure 7.1 Spending Profiles for cost escalation calculations for projects of different lengths.





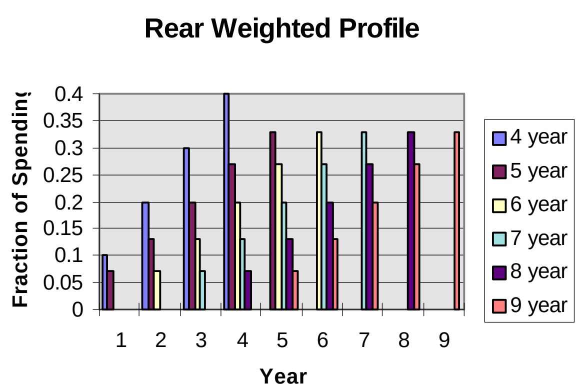
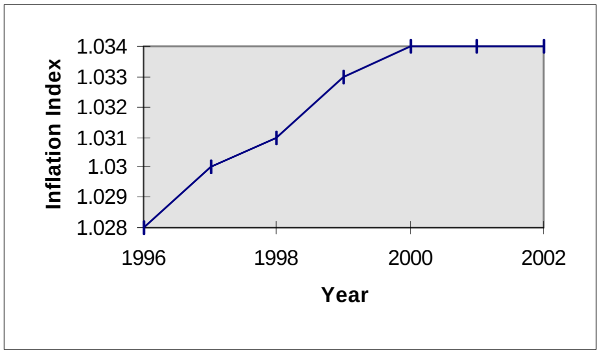


Figure 7.2 Inflation rates used in cost escalation calculation.



Each WBS element also has a total of all the components:

$$C_i = C_{Hard\text{-}i} + C_{Eng\text{-}i} + C_{Lab\text{-}i} + C_{constMan\text{-}i} + C_{engOv\text{-}i} + C_{hardOv\text{-}i} + C_{LabOv\text{-}i} + C_{tax\text{-}i} + C_{cont\text{-}i} + C_{escal\text{-}i}$$

Several cost totals are calculated. These are:

- Total Project Cost (TPC) = sum of all WBS costs, except WBS1.9 (Operations).

- Total Estimated Cost (TEC) = sum of all WBS costs, except WBS1.9 (Operations), WBS 1.1 (R&D) and WBS 1.11 (Other TPC costs).

- Construction Costs (CC) = sum of Hardware + Labor + Installation cost for WBS 1.3 through WBS 1.8.

Construction management costs are treated in a special way. The Project Support construction management costs (in WBS 1.2.1) are input directly. For WBS1.3-WBS1.8, the construction management costs are scaled with the ED&I costs, so that the total construction management cost is 5% of the construction cost. We do not indicate this cost calculation (which is done automatically in the code by use of an iterated equation) in the scalings listed below.

Finally, all cost scalings described below are in 1996 $. Generally, the "direct" cost scalings are derived to fit results of more detailed cost estimates. A benchmark comparison of the accelerator direct cost scalings relative to results from more detailed studies are shown in Appendix 2.

7.2 WBS Cost Scalings:

7.2.1 WBS 1.1. R&D Cost Scalings

These estimates are preliminary as discussed above, and are from the NSNS cost estimate of February 1996. Prior year R&D costs ,expended before line-item status, are included in WBS 1.11.1. Overhead costs have been factored out of the direct cost scalings shown below, and are explicitly added back, as explained above. The scalings with power and current indicated below are optional, and give a simple linear connection between the two power level points which were available for 1-MW and 5-MW beam power. The front end R&D costs cam be optionally scaled with $I_{0\text{-}source}$.

1.1.1 Accelerator front end

Hardware =0

Engineering = $6.30\text{x}10^6 + \left(\frac{I_{0-Source}}{0.035}(A) - 1\right) \times 3.14 \times 10^6$, (for $I_{0\text{-}Source}$ > 35 mA)

Labor factor = 0

ED&I Overhead = 32.25% (Subcontract and Lab)

1.1.2 Linac

Hardware =0, Engineering = $9.65\ \text{x}10^6 + \left(1 + \frac{P_{beam}(MW) - 2.5}{2.5}\right) \times 2.25 \times 10^6$

Labor factor = 0, ED&I Overhead = 32.25% (Subcontract and Lab)

1.1.3 Ring

Hardware = 0, Engineering = $5.17\ \text{x}10^6$, Labor factor = 0, ED&I Overhead = 32.25% (Subcontract and Lab)

1.1.4 Neutron Source

Hardware =0, Engineering = $1.54\ \text{x}10^6$,

Labor factor = 0

1.1.5 Mercury Target

Hardware = 0, Engineering = $4.58\ \text{x}10^6 \left(1 + \frac{P_{beam}(MW) - 1}{1.5}\right) \times 1.4 \times 10^6$

(for P_{beam} > 1 MW), Labor factor = 0

1.1.6 Materials

Hardware =0, Engineering = $5.6\ \text{x}10^6 + \left(1 + \frac{P_{beam}(MW) - 2.5}{2.5}\right) \times 1.4 \times 10^6$,

(for P_{beam} > 2.5 MW), Labor factor = 0

1.1.7 Cold Moderator

Hardware =0, Engineering = $1.6\ \text{x}10^6$, Labor factor = 0

1.1.8 Beam Guides

Hardware =0, Engineering = $6.1\ \text{x}10^6$, Labor factor = 0

1.1.9 I&C

Hardware =0, Engineering = $0.8\ \text{x}10^6$, Labor factor = 0

1.1.10 Robotics

Hardware =0, Engineering = 0.9×10^6, Labor factor = 0

An average contingency of 20 % is applied to R&D WBS elements. The R&D WBS level is escalated using a front end weighted spending profile. Note that prior year R&D costs are included separately in WBS element 1.11.1 which is discussed below.

7.2.2 WBS 1.2. Project Management Cost Scalings

Much of the input to these cost scalings is described above in the project support section, which lists rough levels of required effort. The costs calculated in the project support module are incorporated into the WBS cost structure as follows:

1.2.1 Management and Administration

1.2.1.1 Administration

Engineering cost = Project administration costs described in section 6
Hardware = 0.13 ED&I costs
Labor factor = 0
Engineering Overhead rate = 32.25%

1.2.1.2 Construction Management

Construction management cost = Construction management costs of section 6
Hardware = 0.13 x ED&I costs
Labor factor = 0
Engineering Overhead rate = 5.9%

1.2.1.3 A/E Support

Engineering cost =A/E costs described in section 6
Hardware = 0.13 x ED&I cost
Labor factor = 0
Engineering Overhead rate = 5.9%

1.2.1.4 Other DOE Lab support

Engineering cost = Other DOE Lab costs described in section 6
Hardware = 0.13 x ED&I cost
Labor factor = 0
Engineering Overhead rate = (32.25% + 5.9%+ 32.25%*5.9%) Note that the other lab overhead is taxed with the subcontract tax too.

1.2.2 Systems Engineering

Engineering cost = Systems engineering costs described in section 6
Hardware = 0
Labor factor = 0
Engineering Overhead rate = 32.25%

1.2.3 Safety

Engineering cost =Safety engineering costs described in section 6
Hardware = 0
Labor factor = 0
Engineering Overhead rate = 32.25%

1.2.4 Environmental
Engineering cost = 0.4 M$ for permits + 0.75 M$ for the EIS
Hardware = 0
Labor factor = 0
Engineering Overhead rate = 32.25%

1.2.5 QA
Engineering cost = QA engineering costs described in section 6
Hardware = 0.05 Engineering costs
Labor factor = 0
Engineering Overhead rate = average of the ORNL Lab and sub-contracting rates

1.2.6 Regulator Compliance
Engineering cost = 1.3 M$
Hardware = 0
Labor factor = 0
Engineering Overhead rate = 32.25%

The default contingency for project management is 25%. There is an option to scale the project management costs so that the ED&I fraction of the project management costs is set to a specified fraction of the construction costs. In this case, the costs described above are pro-rated accordingly. The default setting is to scale the project management costs so that the project support ED&I costs are 10% of the construction costs.

7.2.3 WBS 1.3 Front End Systems Cost Scalings

These costs are from the LBNL front end group. To use them in the framework of this model, the LBNL costs were modified as follows: hardware costs were divided by a factor of (1.0 + 0.0825 + 0.030) in order to factor out taxes and hardware overhead, ED&I costs were divided by 1.3225 to factor out ED&I overhead, and the labor and installation costs were divided by 1.069 to factor out the labor overhead.

1.3.1 Front End Ion source
Hardware = 1.12 x 10^5\$ N_{source}
Engineering factor = 0.945 c_{aclEng} , Labor factor = 1.55
1.3.2 LEBT
Hardware = 1.97 x 10^5 \$ N_{source}
Engineering factor = 0.960 c_{aclEng} , Labor factor = 1.45
1.3.3 RFQ assemblies
Hardware = 1.28 x 10^6 \$

Engineering factor = 0.413 c_{aclEng} , Labor factor = 0.758

1.3.3 MEBT

Hardware = 4.66 x 10^5 \$

Engineering factor = 0.503 c_{aclEng} , Labor factor = 0.482

1.3.5 Other costs such as alignment, support, I&C and system integration

Hardware = 0.254 x 10^5 \$

Engineering factor = 1.43 c_{aclEng} , Labor factor = 4.00

An average contingency of 27% is used for WBS 1.3. Also, it is assumed that the ED&I for this level-2 WBS will be done outside of ORNL, and will be subject to a 5.9% subcontract tax, in addition to the nominal 32.25% lab overhead.

7.2.4 WBS 1.4 Linac Cost Scalings

These costs are scaled to match costs from Los Alamos National Laboratory. The ED&I, Hardware, and Labor fractions are taken from the BNL 5-MW design costs [1].

1.4.1 RF Power

Hardware = 0.44 \$/W $P_{maxRFLinac}$. This scaling was derived to fit more detailed costs from LANL for both a 2.5-MW and 1.0-MW linac.

Engineering factor = 0.17 c_{aclEng} , Labor factor = 0.04

1.4.2 Vacuum systems

Hardware = 1.33 x 10^4 \$/m $L_{linacStruct}$

Engineering factor = 0.156 c_{aclEng} , Labor factor = 0.190

1.4.3 RF structures

Hardware = 0.95 x 10^5 \$/m $L_{linacStruct}$

Engineering factor = 0.2 c_{aclEng} , Labor factor = 0.08

1.4.4 Mechanical structures

Hardware = 0.85 x 10^4 \$/m $L_{linacStruct}$

Engineering factor = 0.2 c_{aclEng} , Labor factor = 0.08

1.4.5 Diagnostics

Hardware = 3.6 x 10^3 \$/m $L_{linacStruct}$

Engineering factor = 4.11 c_{aclEng} , Labor factor =4.13

1.4.6 Magnet Power Supplies

Hardware = 8.02 x 10^3 \$/m $L_{linacStruct}$

Engineering factor = 0.060 c_{aclEng} , Labor factor = 0.118

1.4.7 Fixed costs

Hardware = 10.3x 10^6 \$

Engineering factor = 0.11 c_{aclEng} , Labor factor = 0.167

1.4.8 Remote Maintenance costs

Hardware =0, Engineering factor = 0, Labor factor = 0

No remote maintenance cost for the linac is included.

The contingency factor for the linac systems is taken to be 25%. The factor c_{aclEng} is a multiplier applied to the accelerator ED&I costs and is nominal set to 1.0. Also, it is assumed that the ED&I for this level-2 WBS will be done outside of ORNL and will be subject to 5.9% subcontract tax, in addition to the nominal 32.25% lab overhead.

7.2.5 WBS 1.5 Ring Cost Scalings

These cost scalings are derived to fit data from a variety of sources, including the NSNS cost 8/96 exercise, the IPNS-U proposal [2], the BNL 5 MW SNS [1], and the RCS booster ring for the TRIUMF KAON proposal [13]. Breakdown of costs into ED&I, Labor and Hardware fractions follows the BNL RCS values [1].

1.5.1 Beam Transport from Linac to Ring:

Hardware = N_{ring} (1.2 x10^6 \$ (1 + $(B\ )_{inj}$/5.65[Tm]) +
0.68 x10^6 \$ $L_{linac2Ring}$ + 2.5x10^6 \$)
(The first term covers magnets and power supplies, the second term covers vacuum, and the third term covers I&C, scrapers, collimators, and debuncher)
Contingency = 20%
Engineering factor = 0.2 c_{aclEng} ,
Labor factor = 0.64

1.5.2 Injection

Hardware = N_{ring} 2.69 x10^6 \$ per ring
Engineering factor = 0.457 c_{aclEng} , Labor factor = 0.680
Contingency = 25%

1.5.3 Magnets

Contingency = 25%

1.5.3.1Dipoles

Hardware = $N_{ring} N_{dipole} \left(5.25\times10^4 + 1.125\times10^6\, g_{dipole}^2\, l_{dipole}\right)$
Engineering factor = 0.074 c_{aclEng} , Labor factor = 0.33

1.5.3.2 Quadrupoles

Hardware = $N_{ring} \left(10^4 N_{quad} + 8.8\times10^5 L_{quad}\, b_{quadBore}^2\right)$
Engineering factor = 0.087 c_{aclEng} , Labor factor = 0.667

1.5.3.3 Other magnets

Hardware = N_{ring} 4.8 x10^6
Engineering factor = 0.07 c_{aclEng} , Labor factor = 0.36

1.5.4 Power Supplies

Contingency = 20%

1.5.4.1 Dipoles

For accumulator rings, the costs are set = ½ the dipole magnet cost.

For synchrotrons, the power supply costs are set = the dipole magnet costs.

1.5.4.2 Quadrupoles

Hardware = N_{Ring} 6 x10^4 L_{Quad}

Engineering factor = 0.0664 c_{aclEng} , Labor factor = 0.093

1.5.4.2 Other power supplies

Hardware = N_{Ring} 12.5 x10^3 L_{Ring}

Engineering factor = 0.0664 c_{aclEng} , Labor factor = 0.093

1.5.5 Vacuum

Hardware = N_{Ring} (2.55x10^4 L_{Ring}) for accumulator rings,

Hardware = N_{Ring} (3x10^4 L_{Ring}) for synchrotron rings,

Engineering factor = 0.155 c_{aclEng} , Labor factor = 0.190

Contingency = 20%

1.5.6 RF

Hardware = 3.9 x10^6 N_{Ring} + 3.5 x10^6 N_{Ring} $\langle P_{ringBeam} \rangle$

Engineering factor = 0.16 c_{aclEng} , Labor factor = 0.42

This scaling was derived to fit a cost estimate for the NSNS 1 MW Accumulator ring, the IPNS-U proposal and the BNL 5 MW SNS RF proposal cost.

Contingency = 15%

1.5.7 I&C

Hardware = N_{Ring} 3.86 x$10^{6\,+}$ 7.03x10^6 \$ $(N_{Ring}\langle P_{ringBeam}\rangle)^{0.3}$

Engineering factor = 4.20 c_{aclEng} , Labor factor = 5.0

Contingency = 25%

1.5.8 Collimator, radiation safety

Hardware = 2.48 x10^6 \$

Engineering factor = 0.403 c_{aclEng} , Labor factor = 0.302

Contingency = 30%

1.5.9 Extraction system

Hardware = N_{Ring} 2.37x10^6 \$ $\sqrt{\dfrac{B_{ext}}{5.65(Tm)}\dfrac{g_{dipole}}{0.16\,m}}$ per ring

Engineering factor = 0.411 c_{aclEng} , Labor factor = 0.300 factor = 0.49

Contingency = 20%

1.5.10 Transfer to Target

Hardware = $N_{Targets}$ $L_{ring2Targ}$ /150(m) x

$$(2.23 \text{ x}10^6 \text{ \$ } + 1.65\text{x}10^6 \text{ \$ } \sqrt{\frac{B_{ext}}{5.65(Tm)}})$$

The first term covers vacuum, I&C and beam spreader, the second term includes magnets and power supplies.
Engineering factor = 0.49, Labor factor = 0.81
Contingency = 15%

1.5.11 Installation and alignment
Hardware = $N_{Targets}$ 2.6 x10^6\$ (L_{ring}/ 208.5m)
Engineering factor = 0., Labor factor = 1.5
Contingency = 25%

The default contingency factor for the ring systems is taken to be 25%.

7.2.6 WBS 1.6 Neutron Source Systems Cost Scalings

1.6.1 Target and Moderator Systems
1.6.1.1 Solid target assemblies (Not used in NSNS)
Engineering = 0.
Hardware = 0, Labor factor = 0
1.6.1.2 Mercury Targets
Hardware = 0.6x10^6, Engineering factor = 6, Labor factor = 0
1.6.1.3 Target vessel and windows
Hardware = $N_{targets}$ 0.31x10^6
Engineering factor = 0.7, Labor factor = 0.55
1.6.1.4 Ambient moderators
Hardware = $N_{ambientMods}$ 7.34x10^5\$ ($<P_{RingBeam}>/ 10^6)^{0.2}$
Engineering factor = 0.5, Labor factor = 0.25
The cost of the ambient moderator insert cost, used in the replaceable item operational costs, is taken to be 20% of the above hardware cost.
1.6.1.5 Cryogenic moderators
Hardware = $N_{cryoMods}$ 1.94x10^6 \$ ($<P_{RingBeam}>/ 10^6)^{0.2}$
Engineering factor = 0.5, Labor factor = 0.25
The cost of the cryogenic moderator insert costs, used in the replaceable item operational costs, is taken to be 7% of the above hardware cost.
1.6.1.6 Reflectors
Hardware = $N_{moderators}$ 1.58x10^6
Engineering factor = 0.40, Labor factor = 0.15
1.6.2 Neutron beam transport
1.6.2.1 Beam guides
Hardware = 0.6x10^6
Engineering factor = 0.0, Labor factor = 0
1.6.2.2 Beam Shutters
Hardware = 2.5 x10^6
Engineering factor = 0.2, Labor factor = 0, Contingency = 0.4
1.6.2.3 Beam shield

Hardware = $3.6x10^6$
Engineering factor = 0.2, Labor factor = 0.15, Contingency = 0.1

1.6.3 Remote Maintenance
Hardware =$7.81x10^6$
Engineering factor = 0.65, Labor factor = 0.114, Contingency = 0.27
Engineering overhead factor = 0.20 (Part of work is sub contracted).

1.6.4 Controls
Hardware =$0.4 x10^6$
Engineering factor = 1.4, Labor factor = 0.58.

The contingency factor for the target systems is taken to be 25%, unless stated otherwise.

7.2.7 WBS 1.7 Instruments Cost Scalings

1.7.1 Basic scattering and nuclear physics instruments
Hardware = $2.95x10^6$ \$/Basic instrument (includes additional support costs includes by ORNL)
Engineering factor = 0.3, Labor factor = 0.02

These costs are an average of 4 instruments, as provided by H. Mook, 6/96. The contingency factor for the instrument systems is taken to be 25%.

7.2.8 WBS 1.8 Conventional Facilities Cost Scalings

In the conventional facility ED&I costs include some extra "Engineering Support" costs. These costs cover ORNL personnel who will oversee the construction work. These costs are listed in terms of required FTEs (@ 132 k\$/FTE unburdened). A nominal contingency of 25% is applied to all conventional facility costs, unless noted otherwise. Note that many cost items include an adder (CC_{ind}) for the construction contractor indirect costs such as vehicles, profits, etc.

1.8.1 Land Improvements
Labor = $24. \text{ x } 10^6$ \$ $(A_{bldgsFoot}/2.17 \text{ x}10^4 \text{ m}^2) \text{ x } (1+CC_{ind})$
Engineering factor = 0.166 of Labor + Hardware (from ANS)
Contingency = 0.35
Engineering support = 7.2 FTE

1.8.2 Buildings
(These building costs are normalized to those provided by E. Stone, 2/29/96 during the ORNL costing exercise for the NSNS effort).

1.8.2.1 Front End Building
Hardware = $0.35x10^5$ [\$/m] $(1+CC_{ind})$

Engineering factor = 0.33, Labor factor = 1.0
Engineering support = 7.2 FTE (covers all of WBS 1.8.2)

1.8.2.2 Linac Buildings
Hardware = {416 [$/m^2] $A_{bldgLinKly}$ + 526 [$/m^2] $A_{linacPump}$
+ 2.6 x10^3 [$/m] L_{linac} [m]} (1+CC_{ind})
Engineering factor = 0.15, Labor factor = 1.0

1.8.2.3 Ring Buildings
Hardware = {0.9 x10^3 [$/m^2] $A_{ringSup}$ + 0.59 x10^4 [$/m] L_{ring} [m]} x (1+CC_{ind})
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.4 Target Station
Hardware = 0.95 x10^3 [$/m^2] $A_{expHall}$ (1+CC_{ind})
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.5 Transfer Tunnels
Hardware = 2.6 x10^3 [$/m] $L_{transferTunnel}$ [m] (1+CC_{ind})
Engineering factor = 0.33 , Labor factor = 1.0
Contingency = 0.35

1.8.2.6 Beam Dumps
Hardware = 0.71 x10^6 (2. + N_{ring}) [$] (1+$CC_{ind}$)
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.7 Administration Building
Hardware = 3.21 x10^2 [$/m^2] A_{admin} (1+CC_{ind})
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.8 Control Building
Hardware = 3.73 x10^2 [$/m^2] $A_{control}$ (1+CC_{ind})
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.9 Service buildings
Hardware = { 0.31 x10^6 [$] (for FE service bldg.) +
0.5 x10^6 [$] (for linac klystron/magnet testing bldg.) +
0.13x10^6 [$] (for ring service bldg.) +
0.158x10^6 [$] (for electronics testing bldg.) } (1+CC_{ind})
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.10 Research support building
Hardware = 0.563 x10^6 [$] (1+$CC_{ind}$)
Engineering factor = 0.33, Labor factor = 1.0

1.8.2.11 Shielding

Hardware = {1.21 [$/kg] M_{shield} +
0.91 x10^6 [$] (for beam-line shielding) } (1+CC_{ind})
Engineering factor = 0.2, Labor factor = 1.0

1.8.3 Water systems

The basic plumbing costs are calculated from average unit costs derived from the BNL detailed cost estimate.

Hardware = {1780 $/m ($L_{transferTunnel}$ + L_{linac} + L_{ring}) + 115 $/m^2 $A_{bldgtot}$
+7.79x 10^6 [$] ([$P_{maxLinacRF}$ + $P_{ringRF0}$]/ 1.18 x 10^8 W) $^{0.6}$ } (1+CC_{ind})
Engineering factor = 0.15, Labor factor = 0.6
Engineering support = 7.5 FTE.

1.8.4 Electrical systems

Electrical systems cost are scaled with the installed site power capacity.

Hardware = 22 x 10^6 $ (P_{siteAC}/ 48 MVA)$^{0.6}$ (1+CC_{ind})
Engineering factor = 0.17, Labor = 6 x 10^6 $ + 0.23* Hardware costs
Engineering support = 7.9 FTE.

1.8.5 Environmental systems

HVAC costs are calculated from average unit costs for floor area and a fixed cost for the hot cell + clean room HVAC costs.

1.8.5.1 HVAC

Hardware = {1060 $/m ($L_{transferTunnel}$ + L_{linac} + L_{ring}) +
287 $/m^2 $A_{bldgtot}$ } (1+CC_{ind})
Engineering factor = 0.19, Labor factor = 0.626
Engineering support = 7 FTE.

1.8.5.2 Hot Cell HVAC Equip

Hardware = 3.6 x10^6 [$] (1+$CC_{ind}$)
Engineering factor = 0.19, Labor factor = 0.626

1.8.6 Plant service systems

These are additional plant services systems estimated by G. Mcnutt for air, vacuum, compressed gas, steam, and decontamination systems,

1.8.6.1 Fluid systems (additional plant service costs added by ORNL)

Hardware = 4.57 x 10^6 [$] (1+$CC_{ind}$)
Engineering factor = 0.31, Labor factor = 0.84
Engineering support = 4.8 FTE.

1.8.6.2 Cryogenic systems

Hardware = 4 x 10^6 [$] ($P_{cryo}$ /4 x10^5)$^{0.3}$ (1+CC_{ind})

This cost is normalized to the cryogenic power calculated for a 1-MW reference design and includes ED&I.
Engineering factor = 0.13, Labor factor = 0.25

1.8.7 Fire Protection
Fire protection costs are calculated from average unit costs as per the BNL detailed cost estimate.

Hardware = {208 \$/m (L_{tunnel} + L_{ring}) + 33.8 \$/m^2 $A_{bldgtot}$ } (1+CC_{ind})
Engineering factor = 0.58, Labor factor = 1.5
Engineering support = 2.5 FTE.

1.8.8 Plant Rad Wastes

Hardware = 5.1 x 10^6 (1+CC_{ind}) [\$]
Engineering factor = 0.41, Labor factor = 0.524
Engineering support = 5.5 FTE.
Contingency = 30%

1.8.9 Plant I&C

Hardware = 6.38x10^6 [\$] (1+CC_{ind})
Engineering factor = 0.96, Labor factor = 0.134
Engineering support = 11.1 FTE.

1.8.10 General purpose equipment

This category includes items such as signs, furniture, transporters etc., and these costs are taken from ANS . Note that crane costs are not included here since they are in the building costs. Also, remote manipulators are not included.

Hardware = 3.7x10^6 [\$] (1+CC_{ind})
Engineering factor = 0.0833, Labor factor = 0.070
Engineering support = 3.8 FTE.

7.2.9 WBS 1.9 Operations Cost Scalings.

This WBS level is not included in the project cost sums, but rather is included for informational purposes. Also, This information is used in calculating Pre-Operational costs (see 1.11 below). This WBS level includes no contingency. Also, escalation is calculated in the first year of operation at the end of the project. See the Operations section 5 for a description of the numbers of personnel and cost rates for the various categories used for WBS 1.9.

1.9.1Administrative Support
Engineering costs = sum of personnel x rate/year
1.9.2 Management and planning
Engineering costs = sum of personnel x rate/year

1.9.3 Maintenance
Engineering costs = sum of personnel x rate/year
1.9.4 Health and Safety
Engineering costs = sum of personnel x rate/year
Hardware costs = Health equipment used /year
1.9.5 Training
Engineering costs = sum of personnel x rate/year
1.9.6 QA
Engineering costs = sum of personnel x rate/year
1.9.7 Utilities
Hardware costs = electric + steam + water + waste disposal
1.9.8 Replaceable Items
Hardware costs = sum of replaceable item costs
1.9.9Security
Engineering costs = sum of personnel x rate/year
1.9.10 Accelerator operations
Engineering costs = sum of personnel x rate/year
1.9.11 Research Operations
Engineering costs = sum of personnel x rate/year
1.9.12 Initial Purchases
Presently set to zero.

7.2.10 WBS 1.10 DOE Support Costs

1.10.1 DOE Support
Hardware = 0, Engineering = 1.24 M$, Labor factor = 0, contingency = 0
This results in a total 2.0 M$ cost after overhead is added.

7.2.11 WBS 1.11 Other costs included in the TPC

Although these costs are not in the official NSNS WBS, never-the-less they are included in the TPC. These costs are labeled as "1.11"elements, to be consistent with the nomenclature of the model, but we emphasize that these are not part of the NSNS project WBS. The sum of WBS 1.11.1 - 1.11.4 elements is 16 M$, i.e. the expected funding levels for FY 1996 and 1997. These elements have no contingency and escalation.

1.11.1 Prior year R&D
Hardware = 0, Engineering = 6 M$, Labor factor = 0
1.11.2 CDR pre-operation
Hardware = 0, Engineering = 9 M$, Labor factor = 0
1.11.3 Decontamination and Decommissioning
Presently set to 0.
1.11.4 Site Characterization
Hardware = 0, Engineering = 0.76 M$, Labor factor = 0
1.11.5 Environmental Impact Statement (see WBS 1.2.1)
Hardware = 0, Engineering = 0, Labor factor = 0

1.11.6 Pre-operational costs during line item construction

Pre-Operational costs are scaled from the estimate for operation costs (see WBS 1.9 costs). The fraction is estimated of each WBS1.9 level 3 costs required during the entire Pre-Operation phase. The methodology used in obtaining these fractions is described in Appendix II, Pre-Operational Cost Estimate. The Pre-Op fractions of the equilibrium full power annual operational costs used are:

Administrative Support:	104%
Management & Planning:	16%
Maintenance:	205%
Health & Safety:	32%
Training:	292%
QA	330%
Facility Operations:	83%
Research Operations:	150%
Security:	91%

Utility and spare parts costs are taken to be 21 % that of a full year of equilibrium power operation (see Appendix II) . For initial purchases, the hardware costs of one target, one ambient moderator and one cryogenic moderator assembly are included.

WBS elements 1.11.1 through 1.11.5 are not escalated, and have no contingency. WBS 1.11.6 uses a 20% contingency, and assumes a rear-weighted spending profile to calculate the escalation.

8. Figure-of-Merit

Several “Figure-of-Merit” (FOM) calculations are provided as a guide to the cost effectiveness of providing the neutrons. Essentially these FOMs scale as the neutron source rate per cost. The short pulse neutron source rate at the target is estimated as:

$$I_{neutSP} = N_{neut-proton} < I_{Ring} > /e\,,$$

where the number of neutrons per proton ($N_{neut\text{-}proton}$) is estimated as:

$$N_{neut-proton} = 0.1\left(A_{target} + 20\right)\left(\frac{E_{Ring}\,(MeV)}{10^3} - 0.12\right).$$

The worth of these neutrons is estimated in two ways: (1) relative to the capital cost i.e. TPC, and (2) relative to the life-cycle-cost. Relative to the capital cost, the “worth” is calculated as :

$$W_{neut-cap}(neutron / \$ - \sec) = \frac{I_{neutSP}}{TPC}\,.$$

Relative to the life cycle cost (C_{life}), the neutron worth is calculated as:

$$W_{neut-life}(neutron/\$) = \frac{I_{neutSP}}{C_{life} \times 3.15 \times 10^7 \text{ sec}/\ yr},$$

and the life cycle cost is estimated as:

C_{life} ($/yr) = TPC/10 years + Operating Cost/year,

where the operating cost is calculated in the first year of operation dollars.

Glossary of Symbols:

A_{admin}	Office building space [m^2]
$A_{bldgsFoot}$	Total building + tunnel ground footprint area [m^2]
$A_{bldgsTot}$	Total building (without tunnels) floor space area [m^2]
$A_{bldgTest}$	Electronic equip. testing building area [m^2]
$A_{bldgLinKly}$	Linac klystron building area [m^2]
$A_{bldgServ}$	Linac klystron building service / testing area [m^2]
$A_{resSupl}$	Research Support building service / testing area [m^2]
$A_{control}$	Control building area [m^2]
$A_{elecTestl}$	Electrical equipment testing building area [m^2]
$A_{expHall}$	Total experimental hall area [m^2]
$A_{FEService}$	FE service building area [m^2]
$A_{injectHall}$	Injector hall area [m^2]
$A_{linacPump}$	Linac pump building area [m^2]
$A_{linServ}$	Linac service building area [m^2]
$A_{RingGrnd}$	Ring ground buildings area (HEBT, TBST, injection/extraction) [m^2]
$A_{RingService}$	Ring service buildings area (Vacuum + electronics + assembly labs) [m^2]
$A_{RingSup}$	Ring support buildings (HEBT, TBDT, injector + extractor halls) [m^2]
$B_{bendInj}$	Ring bend radius at injection [m]
$B_{bendExt}$	Ring bend radius at extraction [m]
B_f	Bunch factor (longitudinal) for beam in ring.
B_{quad}	Ring quadrupole magnet bore [m]
$B_{quadGrad}$	Ring quadrupole magnet gradient [T/m]
$b_{quadMin}$	Ring quadrupole minimum bore[m]
$B\ _{inj(ext)}$	Beam rigidity (T-m) at injection (extraction)
C_i	Cost for WBS element i [$]
$C_{cont\text{-}i}$	Contingency cost for WBS element i [$]
$C_{engOv\text{-}i}$	Engineering overhead cost for WBS element i [$]

$C_{escal-i}$	Escalation cost for WBS element i [$]
C_{Eng-i}	Engineering cost for WBS element i [$]
$C_{hardOv-i}$	Hardware overhead cost for WBS element i [$]
C_{Hard-i}	Hardware cost for WBS element i [$]
C_{life}	Life cycle cost [$/yr]
$C_{labOv-i}$	Labor overhead cost for WBS element i [$]
C_{Lab-i}	Labor cost for WBS element i [$]
C_{Tax-i}	Tax cost for WBS element i [$]
CC	Construction Costs [B$]
CCL	Coupled Cavity Linac
c_{aclEng}	Multiplier used in accelerator engineering costing
d_{vv}	Distance for vacuum vessel clearance inside magnet aperture [m]
DTL	Drift Tube Linac
e	Unit charge (1.6022x10^{-19} C)
$f_{constMan-i}$	Construction management costs / engineering costs factor for WBS i
f_{cont-i}	Contingency cost factor for WBS i
$f_{escal-i}$	Escalation cost factor for WBS element i.
f_{Eng-i}	Engineering costs / hardware costs factor for WBS i
$f_{engOv-i}$	Engineering overhead costs factor for WBS i
$f_{hardOv-i}$	Hardware overhead cost factor for WBS I
$f_{inflate-i}$	Inflation cost factor for year i, relative to Jan. 1996.
f_{Lab-i}	Labor costs / hardware costs factor for WBS i
$f_{spend-i}$	Spending factor for year i.
$l_{LabOv-i}$	Labor overhead costs factor for WBS i
E_{Linac}	Beam energy after Linac acceleration [MeV]
E_{Ring}	Beam energy after exiting the ring [MeV]
$T_{bunchRFQ}$	RFQ bunching efficiency (=ion source input current / RFQ output current)
$f_{capacity}$	Plant average capacity factor
$f_{dutyChopt}$	fraction of time linac current is on during chopped pulse injection
$f_{dutyMacro}$	Linac injection time / (linac injection + off time)
$f_{dutyMacroRF}$	Linac RF duty factor
$f_{dutyRing}$	RCS acceleration duty factor
$f_{ringACLossRF}$	Ring RF total power / power to beam
$f_{ring-accel}$	Adjusting factor for average voltage seen by proton during ring acceleration.
RCS	Fast Coupling Synchrotron
G_i	Accelerating gradient in linac section i (i = DTL1, DTL2, and CCL) [mV/m]
g_{dipole}	Ring dipole magnet gap [m]
H_{cryo}	Total heat deposited in cryogenic moderators [W]
H_2O_{Usage}	Plant water consumption [m^3/sec]
$L_{RCS2Targ}$	Total length of paths from RCS to dumps, and targets [m]
$<I_{chop}>$	Average chopped pulse current during linac pulse [A],

$<I_{linac}>$	Overall time average current exiting the linac [A].
$<I_{ring}>$	Average current exiting the ring [A].
I_0	Peak linac current from all sources [A]
$I_{0\text{-}source}$	Peak linac current per source [A]
$<I_{linac}>$	Average linac current [A]
IS	Ion source
I_{neuSP}	Neutron production rate at target from ring protons [neutrons/sec].
l_i	Linac structure section i length(i = DTL1, DTL2, and CCL) [m]
l_{dipole}	Length of a single dipole magnet in the ring [m]
l_{drift}	Total length of drift space in the ring [m]
$l_{insertDrift1(2)}$	Length of a single long drift of type 1(2)[m]
$l_{quad1(2,3)}$	Length of a single quadrupole magnet of type 1(2,3)in the ring [m]
$l_{shortDrift}$	Length of a single short drift sections between ring quads- dipoles [m]
L_{dipole}	Total length of dipole magnets per ring [m]
L_{linac}	Total physical length of linac [m].
$L_{linacStruct}$	Total length of linac structures (DTLs + CCL) [m].
L_{other}	Length of non-structure components of the linac (empty spaces etc.) [m]
$L_{transferTunnel}$	Length of linac$\rightarrow$ ring + Ring$\rightarrow$ target + linac$\rightarrow$ dumps tunnels [m]
L_{L2Ring}	Linac to ring tunnel distance [m].
L_{MEBT}	Medium Energy Beam Transport length [m]
L_{quad}	Total length of quadrupole magnets per ring [m]
L_{RFQ}	RFQ length[m]
$L_{ring2Targ}$	Ring to single target tunnel distance [m].
$L_{ring2Dump}$	Ring to dump tunnel distance [m].
L_{ring}	Total Ring circumference [m]
M_{shield}	Total target shield mass [kg]
$n_{harmonic}$	Harmonic number for ring (number chop(chopper) pulses / revolution)
$n_{partRing}$	Total number of particles in ring
$n_{turnsInj}$	Number of ring turns during injection
$N_{ambientMods}$	Number of ambient temperature moderators
$N_{cryoMods}$	Number of cryogenic temperature moderators
N_{dipole}	Number of dipole magnets per ring
$N_{dipole\text{-}HL}$	Number of dipole magnets per ring half period
$N_{insertDrfift\text{-}HL}$	Number of insert drifts per ring half period (can be type 1 or 2)
$N_{neut\text{-}proton}$	Number of neutrons produced per proton
N_{quad}	Number of quadrupole magnets per ring
$N_{quad\text{-}HL}$	Number of quadrupole magnets per ring half period
N_{RFRing}	Number of RF cavities per ring
$N_{shortDrfift\text{-}HL}$	Number of short drifts per ring half period
N_{source}	Number of ion sources
N_{ring}	Number of rings
$N_{ringTrans}$	Number of revolutions around synchrotron during acceleration

N_{target}	Number of targets
$<P_{beam-i}>$	Average power to the beam in linac section i (i = DTL1, DTL2, and CCL) [W]
P_{beamLP}	Average power of an additional (optional) long pulse linac [W]
$P_{beamRing}$	Average power of the final beam at ring exit [W]
$P_{beamTot}$	Average total beam power [W]
P_{bldgs}	HVAC, lights, etc. power requirements for buildings and tunnels [W]
P_{BOP}	Misc. power needs for the Balance Of Plant [W]
P_{cryo}	Power to run the cryogenic equipment [W]
$P_{dipoleTot}$	Total power requirement per ring dipole system, magnets, choppers, AC losses etc.[W]
$<P_{linac-wp}>$	Average wall plug power for the linac [W]
$P_{maxlacRF}$	Peak RF power requirement for the linac [W]
P_{pump}	Coolant pumping power for plant [W]
$P_{quadTot}$	Total power requirement per ring quadrupole system, magnets, choppers, AC losses etc.[W]
P_{RF0-i}	Peak power to linac component i= DTL1, DTL2, and CCL [W]
$<P_{RF-I}>$	Average power to the linac component i= DTL1, DTL2, and CCL [W]
P_{RFwp-i}	Average wall plug power for linac section I (i = DTL1, DTL2, and CCL) [W]
$<P_{RFQ}>$	Average RFQ power to beam [W]
$<P_{RFQ-wp}>$	Average RFQ wall plug power [W]
$<P_{struct-i}>$	Average power loss in linac structure section i (i = DTL1, DTL2, and CCL) [W]
$P_{ringMag}$	Total magnet power requirement per ring [W]
$P_{shunt-i}$	Peak Cu power loss in linac section i (i = DTL1, DTL2, and CCL) [W]
P_{site}	Site typical resistive power use [MW]
$P_{siteInst}$	Site installed resistive power capacity [MW]
P_{siteAC}	Site installed MVA capacity [MVA]
$P_{ringBeam0}$	Peak RF power to beam in ring [W]
$<P_{ringBeam}>$	Average RF power to beam in ring [W]
$<P_{ring-wp}>$	Average wall plug power for the ring RF [W],
$P_{ringMag}$	Average synchrotron magnet power [W]
$P_{ringRF0}$	The peak RF power requirement for rings [W]
R_{accept}	Ratio of the allowable ring magnet acceptance to beam emittance.
r_{bend}	Ring bend radius [m].
RFQ	Radio Frequency quadrupole
r_p	Classical proton radius [m].
$R_{shunt-i}$	Shunt resistance/length of linac section i (i = DTL1, DTL2, and CCL) [MOhm/m]
S_{ring}	Ring super-periodicity
$T_{bunchRFQ}$	RFQ bunching transmission factor (=output current/input current)
$T_{lossInject}$	Particle loss fraction during ring injection

macro	Time the linac macro pulse is on (sec)
TEC	Total Estimated Cost [B$]
TPC	Total Project Cost [B$]
V_{maxCav}	Ring RF cavity peak voltage [V]
V_{RFTot}	Total RF voltage around the ring [V]
$V_{RFTotReq}$	Total RF voltage required around the ring to match dB/dt [V]
v_{linac}	Beam velocity after linac acceleration [m/s]
$<v_{Ring}>$	Average beam velocity in the ring [m/s]
v_{ring}	Ring beam velocity at extraction [ms/]
$W_{neut\text{-}Cap}$	Worth of neutrons relative to the capital cost [neutrons/$/sec]
$W_{neut\text{-}life}$	Worth of neutrons relative to the life-cycle cost [neutrons/$]
ring	Ring acceptance
inj	Relativistic factor at ring injection (v_i/c)
ext	Relativistic factor at ring extraction (v_i/c)
dipole	Dipole peak beta value [m]
quad	Quadrupole peak beta value [m]
ΔE_i	Energy gain in linac section i (i = DTL1, DTL2, and CCL) [eV]
ΔE_{RFQ}	Energy gain in the front end RFQ [eV]
ΔE_{Ring}	Energy gain in synchrotron [eV]
ext	Ring beam emittance at extraction [π-m-rad]
inj	Ring beam emittance at injection [π-m-rad]
AC2DC	Linac RF AC to DC efficiency
RFQ	Wall plug to beam RFQ efficiency
RF	Linac RF klystron efficiency
inj	Relativistic factor at ring injection
ext	Relativistic factor at ring extraction
i	Phase angle between bucket and voltage in linac section i (i = DTL1, DTL2, and CCL) [deg]
s	Phase angle between bucket and voltage in the ring
chop	Pulse time of single linac chop pulse [sec]
accel	Acceleration time in a ring [sec]
macro	Pulse time of linac macro pulse [sec]
chop	Chopper pulse time of linac [sec]
macro	Total pulse rate of ring(s) to target [Hz]
chop	Chopper pulse rate during linac injection [Hz]
extract	Extraction Ring RF frequency [Hz]
inject	Injection Ring RF frequency [Hz]

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Appendix 1. Magnet Size and Power Models

A1.1 Dipole magnet model

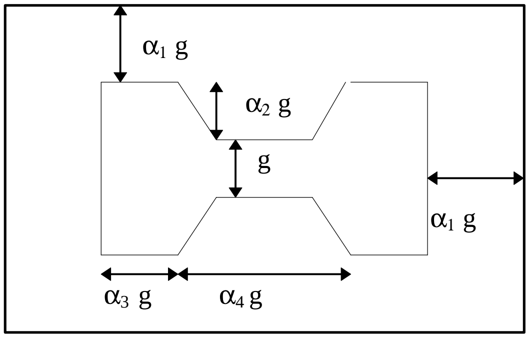

Figure A1.1 Schematic cross section of the dipole geometry.

The dipole magnet sizes and power requirements are estimated following the cross sectional model of A. Ruggiero [14]. The geometry is shown in figure 1.2. The default values for the shape parameters (α_i) are: α_1 = 1.5, α_2 =α_3 = 1, and α_4 = 2. The dipole gap (g_{dipole}) is specified, and the size and powers are subsequently calculated (note that below we describe limits calculated for the magnet gap size). The volume of the dipole iron material is then:

$$V_{dipoleFe} = l_{dipole}\, g^2_{dipole} \left\{ \left(2\ {}_1 + 2\ {}_2 + 1\right)\left(\left(2\ {}_1 + 2\ {}_3 + \ {}_4\right)\right) - \left(\left(4\ \ 2\ {}_3 + 2\ {}_3 + \ {}_4\right)\right) \right\},$$

and we assume a density of 7800 kg/m^3 to calculate the iron mass. In order to calculate the power requirements, the RMS dipole field is first calculated, namely

$$B_{RMS} = \sqrt{B^2_{DC} + \frac{B^2_{AC}}{2}}\,,$$

where the DC dipole field is ½($B_{bendExt}$ + $B_{bendInj}$) and the AC component is ½($B_{bendExt}$ - $B_{bendInj}$). (Note that for the accumulator ring, $B_{bendExt} = B_{bendInj} = B_{RMS}$.) The average current requirement for the ring dipole is then

$$I_{dipoleRMS}(A) = \ \ {}_0 B_{RMS}(T)\, g_{dipole}(m)\,.$$

Assuming a current density in the copper of J_{dipole} (nominally 1.4 MA/m^2), the copper volume is:

$$V_{dipoleCu}(m^3) = \frac{I_{dipleRMS}\, 2\left(l_{dipole} + \frac{\ {}_3 + \ {}_4}{2}\, g_{dipole}\right)}{J_{dipole}}$$, and the power consumption is

$$P_{dipoleCu}(W) = \frac{I_{dipleRMS} J_{dipole} \quad {}_{cu} 2\left(l_{dipole} + \frac{{}_3 + {}_4}{2} g_{dipole} \right)}{J_{dipole}}$$, where

= the copper resistance (=1.72x10^{-8}Ohm-m). The total ring dipole power requirement is scaled form this value as:

$$P_{dipoleTot}(W) = N_{dipole} P_{dipoleCu} \left(2.5 + \frac{\frac{dB_{bend}}{dt}(T/s)}{40} \right)$$

The first factor of 2.5 accounts for “DC adders” such as losses in choke coils, power supplies etc. The second factor in the term in parenthesis accounts for “AC adders” due to induced AC losses associated with the pulsing of these coils. This factor is derived to match the results from the proposals for the BNL 5MW synchrotron and the 1MW IPNS-Upgrade.

Appendix 2. Comparison of the Model Accelerator Costing with Other Benchmarks

The results of the cost scalings for the accelerator components are compared to more detailed estimates here. For this comparison we only consider the direct cost elements of material, ED&I and labor. The comparison points are (1) The NSNS reference as of 8/96, (2) the BNL 5 MW Spallation neutron source pre-conceptual design [1], (3) The IPNS - 1MW upgrade proposal [3], and (4) the TRIUMF KAON factory proposal [13]. Results of this cost comparison are shown in Table A2.1, below. There is good agreement on the WBS level 2 such as the entire ring or linac. At lower WBS levels, there is more disagreement. This disagreement tends to cancel however, when averaged over the entire WBS level 2.

Table A2.1: Comparison of the direct (Hardware, ED&I + labor) costs between the model and several more detailed design studies (all costs are in 1996 M$).

	NSNS Accumulator Ring		**BNL 5 MW RCS**		**IPNS-Ugrade 1 MW RCS**		**TRIUMF** (7) **Booster "B" RSC**	
	Reference	Model	Reference	Model	Reference	Model	Reference	Model
1.3 Front End	**7.1**	**6.4**	**5.0**	**6.4**	**3.3**	**6.4**		
1.4 Linac	**157.1**	**154.8**	**99.5**	**113.6**	**60.0**	**73.9**		
RF Power	63.8	63.7	36.7	49.6	24.9	41.9		
Vacuum		7.5	6.6	4.9		2.0		
RF +Mech Struct (4)	61.7	56.2	38.7	37.2	25.3	14.8		
Mag. power supplies	4.2	3.9		2.6		1.0		
Diagnostics +controls	23.3	12.6	15.0	8.3	3.4	3.3		
Fixed + other costs	4.1	11.0	2.5	11.0	6.4	11.0		
1.5 Ring & Transfer	**87.7**	**87.7**	**205.6**	**266.9**	**93.7**	**93.3**	**50.3**	**68.2**
1.5.1 HEBT	10.4	11.6	3.4	23.4	9.4	9.1		
1.5.2 Injection (2)	4.8	5.8	8.1	5.8	1.8	5.8		5.8
1.5.3 Magnets	13.8	13.7	46.8	45.0	17.9	14.8	8.0	11.4
Dipoles	4.2	4.3	17.3	21.6	6.6	4.5	4.5	3.1
Quads	2.8	2.5	11.4	9.7	3.0	3.4	1.4	1.5
Other	6.9	6.9	18.2	13.7	8.4	6.9	2.1	6.9
1.5.4 Power Supply (6)	7.0	7.1	25.8	37.5	15.6	9.3	7.8	7.6
Dipole	2.1	2.2	11.6	21.6	5.7	4.5	3.9	3.1
Quad	1.9	1.9	8.4	5.3	3.6	2.0	2.3	1.4
Other	3	3.0	5.8	10.5	6.3	2.8	1.7	3.1
1.5.5 Vacuum	7.6	7.1	31.2	28.9	7.7	7.6	6.9	8.6
1.5.6 RF (5,6)	6.1	6.1	29.4	35.3	16.6	10.5	20.1	7.4
1.5.7 I&C (1)	12.0	12.4	27.1	24.8	14.2	12.4	1.8	12.4
1.5.8 Collimator	3.9	4.2	2.4	4.2		4.2		4.2
1.5.9 Extraction (2,3)	4.3	4.1	26.7	15.2	3.4	5.9	5.5	4.1
1.5.10 TDBT	9.0	9.3		24.2	7.2	7.8		
1.5.10 Cable System	2.5							
1.5.10 Install & Alignmen	6.5	6.5	4.6	22.7		5.9	0.2	6.7

1 - BNL 5MW value = 2 x published value since I&C cost for one ring was neglected
2 - BNL 5MW number includes transport to RCS
3 - IPNS costs are distributed in magnet + power supply costs
4 - IPNS number includes vacuum
5 - The Triumph RF system is sized to handle 3 times higher beam power than is used.
Also, the Triumph ring uses a harmonic number of 45, and a frequency ~50 times higher than the other systems.
6. The IPNS-U uses a dual frequency system.
7 - Only the Syncrotron booster ring costs are compared here (the HADRON factory includes several rings).

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